

FORMATION AND EVOLUTION OF THE TRANS-NEPTUNIAN BELT AND DUST

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Abstract

Trans-Neptunian objects (TNOs) with diameter greater than 100 km currently moving in not too eccentric orbits could be formed directly by the contraction of large rarefied condensations. Along with the gravitational influence of planets, gravitational interactions of TNOs played a certain role in their orbital evolution as well. More than 20% of Earth-crossing objects could have come from the trans-Neptunian belt. TNOs and Centaurs (invisible comets mainly beyond Jupiter) could produce an important contribution to the dust content of the interplanetary dust cloud.

Keywords: the Edgeworth-Kuiper belt, interplanetary dust, formation, evolution

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Introduction

So far more than 400 trans-Neptunian objects (TNOs) are known. Jewitt et al. (1996) estimated the total mass of the present Edgeworth-Kuiper belt (EKB) for objects with $30 \leq a \leq 50$ AU to be $0.06m_{\oplus}$ to $0.25m_{\oplus}$, where m_{\oplus} is the mass of the Earth. For TNOs with $a \leq 50$ AU, the average values of eccentricity and inclination are evaluated to be $e_{av} \approx 0.1$ and $i_{av} \approx 8^{\circ}$, respectively. Objects moving in highly eccentric orbits (mainly with $a > 50$ AU) are called "scattered disk objects" (SDOs). For SDOs $e_{av} \approx 0.5$ and $i_{av} \approx 16^{\circ}$. The total mass of SDOs in eccentric orbits between 40 and 200 AU has been estimated by different authors in the range $(0.05 - 0.5)m_{\oplus}$. According to Duncan et al. (1995), about 10- 20% TNOs with $a < 50$ AU left the EKB during the last 4 Gyr under the gravitational influence of planets, and about 1/3 of Neptune-crossing objects could reach Jupiter's orbit during their lifetimes. For a detailed review of the formation and migration of celestial bodies in the Solar system, see Ipatov (2000).

The sources of the interplanetary dust (IPD) cloud cannot be entirely reduced to comets and asteroids alone. Several factors indicate that the overall dust production rate from TNOs may not be negligible compared to that of comets and hence a third important component of the IPD cloud (besides interstellar grains) might be the EKB, or 'kuiperoidal' dust. In our opinion, the EKB influences the formation of the IPD cloud in two ways: (i) as a source of small-size particles slowly drifting toward the Sun under a combined action of the Poynting-Robertson drag and perturbations from the planets; and (ii) as a source of millions of comets between Jupiter and Neptune (Levison & Duncan, 1997; Ozernoy, Gorkavyy, & Taidakova, 2000a), which, in turn, serve as additional sources of dust. The dust can be produced due to evaporation of the volatile material from the TNO surface as a result of a variety of processes, such as the Solar wind and the heating by the Sun, micrometeor bombardment, mutual collisions of kuiperoids, etc.

Formation of the trans-Neptunian belt

Stern (1996), Stern and Colwell (1997), Davis and Farinella (1997), and Kenyon and Luu (1999), among others, investigated formation and collisional evolution of the EKB. In their models, the process of accumulation of TNOs in the massive EKB took place at small (usually about 0.001) eccentricities. Ipatov (2000) found that, due to the gravitational influence of the forming giant planets and the mutual gravitational influence of planetesimals, such small eccentricities could not exist during all the time needed for the accumulation of TNOs. In Ipatov's runs the maximal eccentricities of TNOs always exceed 0.05 during 20 Myr due to the gravitational influence of the giant planets. Eneev (1980) hypothesised that large TNOs and the planets were formed by the accumulation of large rarefied dust-gas condensations, which later contracted to a solid body density. We do not think that all the planets could form in such a way; however, TNOs with diameter $d \geq 100$ km could be formed mainly by the contraction of large rarefied dust condensations, and not by the accretion of smaller solid planetesimals. Perhaps, the largest asteroids and planetesimals with $d \geq 100$ km in the zone of the giant planets could be formed in the same way, while a part of smaller objects could be mainly debris of larger objects and another part could be formed directly by contraction of condensations. Even if the sizes of initial condensations, which had been formed, due to gravitational instability, from the circumsolar dust disk, were about the same at some time at the same distance from the Sun, it would be, due to mutual interactions, a distribution in masses of the final condensations, which then contracted into planetesimals. As in the case of accumulation of planetesimals, there could be a "run-away" accretion of condensations. Possibly, during the time needed for contraction of condensations into planetesimals, some largest final condensations could reach such masses that they formed planetesimals as large as several hundred kilometers.

During accumulation of the giant planets, planetesimals of large eccentricities with the total mass of several tens m_{\oplus} could move from the feeding zone of the giant planets to the trans-Neptunian region (Ipatov, 1987, 1993). These planetesimals increased eccentricities of orbits of 'local' TNOs, which initial mass could exceed $10m_{\oplus}$, and swept most of them. A small portion of such planetesimals could survive in eccentric orbits beyond Neptune's

orbit and become SDOs. The total mass of the planetesimals that came from behind Jupiter’s orbit during formation of the giant planets and then collided the Earth is about the mass of water in the Earth’s oceans (Ipatov, 1995). Dynamical lifetimes of most planetesimals located inside Neptune’s orbit were less than 100 Myr, while those for the objects beyond Neptune were much larger. Therefore, the objects that came from eccentric orbits located mainly beyond Neptune’s orbit, were dominating at the end of an intense bombardment of terrestrial planets, which finished 4 Gyr ago.

Collisional evolution of the trans-Neptunian belt

Frequency of collisions of bodies in the EKB and in main asteroid belt (MAB) was evaluated by Stern (1996), Davis and Farinella (1997), Durda and Stern (2000), and Ipatov (1995, 2000). It is assumed that there are about 106 asteroids with $d \geq 1$ km in the MAB, and the number of asteroids with $d > D_*$ is proportional to $D_*^{-\alpha}$, with α between 2 and 2.5 (Binzel *et al.*, 1991). In the MAB for the ratio s of masses of two colliding bodies, for which a collisional destruction of a larger body takes place, equal to 10^4 , a collisional lifetime T_c of a body with $d = 1$ km is about 1 Gyr (Ipatov, 1995). If $\alpha = 2$ and $s = \text{const}$, then a value of T_c does not depend on d . It is considered that for near-Earth objects (NEOs) $\alpha > 3$ at $d < 40$ m. If it so also for the MAB, then $T_c < 2$ Myr for 1-m rocky asteroid (Ipatov, 1995). At $\alpha = 2$, $s = 10^3$, and the mass of the EKB $\sim 0.1m_\oplus$ for TNOs with $d \geq 100$ km, one gets $T_c = 30$ Gyr. For $s = 10^4$ (and $\alpha = 2$) the values of T_c are smaller by a factor of 4.6 than those for $s = 10^3$. An 1-km TNO collides with one of 10^{12} 100-m objects on average once in 3 Gyr. Therefore, at $s = \text{const}$, the values of T_c for 1-km TNOs are of the same order of magnitude as those for main-belt asteroids.

The total mass of SDOs moving in highly eccentric orbits between 40 and 200 AU is considered to be of the same order or greater than the total mass of the EKB, and the mean energy of a collision of a SDO with a TNO is greater (probably, by a factor of 4) than that for two colliding TNOs of the same masses. Therefore, though SDOs spend a smaller part of their lifetimes at distances $R < 50$ AU, the probability of destruction of a TNO with

$30 < a < 50$ AU by SDOs can be of the same order of magnitude (possibly, even larger) than that by TNOs.

Ipatov (1995, 2000) showed that during the last 4 Gyr several percents of TNOs could change their semimajor axes by more than 1 AU due to the gravitational interactions with other TNOs. First estimates of gravitational interactions between TNOs were made by Ipatov long before the first TNO was found in 1992. Even small variations in orbital elements of TNOs due to their gravitational influence and collisions could cause large variations in orbital elements of TNOs under the gravitational influence of planets (Ipatov and Henrard, 2000).

Migration of bodies to the Earth

The orbital evolution of a hundred TNOs under the gravitational influence of planets is described by Ipatov (1999, 2000) and Ipatov and Henrard (2000). During the evolution, the perihelia of orbits of two test objects decreased by 1 AU during 25 and 64 Myr, respectively. Numerical integration of the average time interval, during which an object crosses Jupiter's orbit during its lifetime, is 0.2 Myr; the fraction of Jupiter-crossing objects (JCOs), which reach the Earth's orbit during their lifetimes amounts to 0.2; and the average time, during which an JCO crosses the orbit of Earth, is about 5000 yr. Using these results, Ipatov (1999, 2000) found that if the number of 1-km EKBOs is as large as 10^{10} (Jewit et al., 1996), then the number of present JCOs of $d \geq 1$ km that came from the trans-Neptunian belt amounts to $3 \cdot 10^4$, and about 170 former TNOs cross both the orbits of Earth and Jupiter. These objects represent about 20% of ECOs, if the number of 1-km Earth-crossing objects is 750. A lot of former TNOs can move in Encke-type orbits with aphelia inside Jupiter's orbit. If nongravitational forces are included into interactions (in impulse approximation), the rate at which objects could be decoupled from Jupiter and attain orbits like those of NEOs is increased by a factor of four or five (Asher et al., 2001).

Modeling of the interplanetary dust

Until recently, the main stumbling block to implementing the comprehensive study of IPD has been the absence of a physical model for the IPD cloud. Such a model would establish a link between the observable characteristics of the zodiacal cloud and the dynamical and physical properties of the parent minor bodies of the Solar system. A preliminary physical model of the IPD cloud based on a new computational approach elaborated by Gorkavyi, Ozernoy, Mather, & Taidakova is described in detail by Ozernoy (2001). This approach permits with modest computational resources to integrate trajectories of hundreds of particles and to effectively store up to $10^{10} - 10^{11}$ particle positions as if they were real particles, which provides a high fidelity 3D distribution of the dust. An appreciable increase in statistics, compared to e.g. Liou & Zook (1999), brings a factor of 10^4 improvement in the detail of a model and enables us to model the IPD cloud at a qualitatively new, 3-D level. Moreover, our approach makes it possible to study, besides stationary processes, certain non-stationary processes as well, e.g. evolution toward steady-state distributions, dust production from non-steady sources, decrease in particle size (due to evaporation and sputtering) and number (due to collisions), etc.

The numerical codes employed account for the major dynamical effects that govern the motion of IPD particles: the Poynting–Robertson drag and solar wind drag; the solar radiation pressure; particle evaporation; gravitational scattering by the planets; and the influence of mean-motion resonances.

The simulated distribution of kuiperoidal dust

The efficiency and power of the employed codes mentioned in the previous section, has been demonstrated by performing the following simulations: (i) distribution of the scattered comets, which enables one to reveal the four ‘cometary belts’ associated with the orbits of four giant planets (Ozernoy et al., 2000a), which are expected to contain 20-30 million of cold comets; (ii) detailed analysis of a rich resonant structure found in these belts, which predicts the existence of gaps similar to the Kirkwood gaps; (iii) a 3-D physical model of

the IPD cloud, which explains the available data of Pioneers and Voyagers dust detectors; (iv) zodiacal light distribution in the Solar system, which fits the COBE data with an average accuracy of 0.85%, and (v) resonant structure in dusty circumstellar disks of Vega and Epsilon Eridani (Ozernoy et al., 2000b) and a warp in dusty disk of Beta Pictoris considered to be a signature of embedded extrasolar planets.

Under a set of reasonable assumptions, it seems safe to conclude:

1. The kuiperoidal dust plays a role more important than previously recognized. It appears to account for the space dust observations beyond 6 AU, while near Earth it could possibly contribute as much as 1/3 of total number density (1/4 of surface density) and 1/3 of the zodiacal emission near ecliptic.
2. The two other components of the IPD cloud, the cometary and asteroidal dust contribute respectively 36% and 30% of the number density and the zodiacal emission (at ecliptic) near Earth. The cometary particles contribute 60% to the surface density of the IPD cloud near Earth. A solely two-component model (i.e. without the kuiperoidal dust) would give a worse fit of dust distribution at Earth and would fail entirely for the outer Solar system.
3. Further improvements in the IPD modeling will include, among others, particles of different sizes, account for evaporation and sputtering of dust as a function of heliocentric distance, and include short-term (days to months) variability and small-scale phenomena in the zodiacal cloud.

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